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HEAT FLUX TRANSDUCER CALIBRATION: SUMMARY OF THE 2nd WORKSHOP

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DEPARTMENT OF COMMERCE ★ UNITED STATES OF AMERICA ★

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ABSTRACT

The second workshop on heat flux gauge calibration was organized to share the results of an effort to expand competence at NIST, and to examine the recommendations made at a previous workshop on heat flux gauge calibration. Over 40 attendees were drawn from U.S. industry, academia, and government organizations. Representatives of a spectrum of industries that rely upon accurate measurement of heat flux described their applications and calibration needs. Presentations were made by Pratt & Whitney, Arnold Engineering Development Center, Ktech Corporation, Lucent Technologies, and Boeing Commercial Airplane Company. A panel of heat flux gauge manufacturers that included representatives of Vatell Corporation, Medtherm Corporation, Concept Engineering, and RdF Corporation gave the perspective from their industry. The efforts being undertaken in Europe to standardize heat flux calibration methods for fire safety standards were also discussed. Explanations and tours of NIST heat flux calibration laboratories were conducted by NIST staff. Discussions among all participants were organized around special considerations and calibration needs of heat flux measurement devices for three different situations: (1) convection dominated, moderate temperature, quasi-steady environments with size and cost as major constraints; (2) convection dominated, high temperature, transient environments with small size and accuracy highly desirable; and (3) radiation dominated with high flux levels, with applications constrained by regulations. Recommendations for future actions and the parties responsible are given at the end of this report.

Key words: **calibration; conduction; convection; gauge; heat flux; measurements; radiation; sensor**

ACKNOWLEDGEMENTS

This document summarizes the presentations and deliberations of a diverse group of people with a common interest in the accuracy of heat flux measurements. The editor has extracted loosely from some and verbatim from others, and acknowledges substantial contributions from K. Azar of Lucent, F. Soechting of Pratt & Whitney, J. Coblish and C. Kidd of AEDC, J. Deane of Boeing, N. Keltner of Ktech, T. Diller of Virginia Tech, and K. Steckler, C. Womeldorf, D. Holmberg, R. Saunders, B. Tsai, A. Murthy, and D. Blackburn of NIST. In addition, the editor thanks all those who attended the workshop and voiced their opinions.

DISCLAIMER

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BACKGROUND

The need for improved heat flux calibration methods was formally recognized by researchers at the National Institute of Standards and Technology (NIST) in 1994, when a program was established to expand the capabilities of the radiometric facilities and to build competence in convective heat flux measurements. The primary motivation was that although NIST facilities were not originally developed specifically for heat flux, gauges were often distributed by their manufacturer with calibrations traceable to NIST radiometric standards. The sensitivity of the calibration to the view angle, wavelength, and total radiant power at levels greater than provided by the radiometric standards was not addressed during the course of normal calibration. Further, even heat flux gauges calibrated in the radiant mode over the required range of view angles, wavelengths, and flux levels could yield errors as high as 40% in applications when convection dominates (Moffat and Danek, 1995; Holmberg et al., 2000). Since comparable convective heat transfer calibration services did not exist at NIST, the user faced an unknown uncertainty in measurement for convective environment applications.

Specific goals of the NIST program were to improve measurement methods for performance of products and fire control technologies; to build competence and advance facilities for calibrating heat flux gauges in pure conduction, convection, and radiation modes; to serve industry, academic, and government needs for interpretation of heat flux measurements and traceable calibration standards; and to reduce uncertainty in heat flux measurements that have significant economic impact on acceptance of materials.

A workshop on heat flux gauge calibration was sponsored by NIST and the National Science Foundation in 1995 to help formulate an approach to reach the goals above. Forty-eight practitioners, designers, and academic experts in the field of heat flux measurements participated, and were charged with identifying geometries, ranges of conditions, and accuracy requirements for a national facility, and with suggesting means to qualify the performance of the facility for the potential users. The organizers of the workshop posed a number of questions for discussion:

- What types of sensors do you use (size, water-cooled)?
- What range of temperature, velocity and heat flux do you measure?
- Are transients important; if so, how fast?
- What modes of heat transfer exist in your applications?
- What accuracy do you require before data become useful?
- How do you currently calibrate your heat flux sensors?
- Should there be a national calibration facility for heat flux sensors?
- What information should be provided for a calibration record; what is the maximum turn-around time and price you can tolerate before forgoing calibration?
- What does "heat flux" mean in a calibration situation; i.e., actual heat flux with a sensor present, or the flux that would exist in the absence of a sensor?

A written report (Moffat and Danek, 1995) summarized the workshop and recommended (1) the establishment of a NIST/industry steering committee to adapt radiometric standards to heat flux standards; and (2) the development of a boundary layer convective heat transfer calibrator, emphasizing accuracy (at expense of transient and high flux conditions). Based upon the outcome of the first workshop, the capabilities of the NIST staff, and internal priorities, the following objectives were established for completion by the end of 1999:

- to enhance the flux levels in the radiometric facility to 200 kW/m^2 with a greater control of view angle and higher level of accuracy;

- to develop the first-ever primary calibration platform for a convective boundary with heat transferred at a rate up to 5 kW/m^2; and
- to develop a non-contact conduction device capable of controlled heat flux levels up to 100 kW/m^2, and with a radiant contribution of less than 2 %.

As of July, 1999, the radiation flux and accuracy goals have been met. The facility currently consists of three apparatus: a 25 mm diameter graphite blackbody cavity with a maximum temperature just under 3000 K; a 50 mm aperture spherical blackbody capable of exposing gauges to a near hemispherical view, limited in temperature to below 1400 K; and a high power laser facility for characterizing transfer standard electrical substitution radiometers. Several sensors have been calibrated up to 55 kW/m^2 using the NIST transfer calibration method. Significant convection effects have been noted in the spherical blackbody, making absolute calibration difficult, although transfer calibration is still feasible. A fourth apparatus, a 50 mm diameter graphite blackbody cavity with a temperature limit of 2800 K, is also in development to extend the radiative flux levels to above 200 kW/m^2. The assessment and minimization of convection effects are in progress, and means to deliver a secondary calibration service in a more economical and rapid manner to the customer are being considered.

The new convection calibration facility is described fully in a later section. Briefly, it consists of a 10 mm by 30 mm channel with an electrically heated lower wall. Air at room temperature flows through a converging nozzle designed to produce a close to top-hat, low turbulence intensity velocity profile at the entrance to the channel. The system isolates convection from radiation to allow the comparison of calibrating the same sensor in different environments. The expanded relative uncertainty (k=2) in wall heat fluxes up to 5 kW/m^2 is $\pm$ 2.8 %, with a 95 % confidence level. Radiation exchange between the sensor and surroundings is minimized by matching the temperature of the top wall to the bottom wall. The facility is automated, operates with redundant sensor and reference locations, and is suitable for calibration of water-cooled or non-water-cooled gauges of various design.

In the conduction calibration rig, a 100 mm diameter flat copper plate at high temperature transfers heat across a small gap filled with helium to a water-cooled cooper plate in which the heat flux gauge is mounted. The apparatus was designed with the following goals: a maximum heat flux of 100 kW/m^2; radiation heat transfer less than 2 % of the conduction; non-surface-contact heat transfer; an expanded uncertainty (k=2) of $\pm$ 5 % with a 95 % confidence level; and the ability to accommodate cooled and uncooled gauges up to 12 mm diameter. (Details on the device are given in a following section.) To date, both Gardon and thermopile-type gauges have been evaluated in nitrogen atmospheres at total fluxes up to 20 kW/m^2, and with helium at flux levels as high as 85 kW/m^2. The agreement between the conduction and convection calibration was within 5 % for the first thermopile gauge tested. The uncertainties need to be better quantified. Modeling of the device using a three-dimensional, transient numerical code is currently underway.

THE 1999 WORKSHOP

The second workshop on heat flux gauge calibration, held at NIST on July 19 and 20, 1999, was organized to share the results of the NIST competence building effort, and to reexamine the recommendations made at the previous workshop. How had the heat flux measurement needs of industry changed? What were the implications for the gauge manufacturers and calibration services? Should NIST continue its current direction? What is the best way to interact with manufacturers, university researchers, and government laboratories?

The workshop was free and open to all who were interested in heat flux calibration issues. Over 40 attendees were drawn from U.S. industry, academia, and government organizations. Karen Brown, Deputy Director, NIST, welcomed the participants, and William Grosshandler of NIST provided the context and goals for the workshop. Representatives of a spectrum of industries that rely upon accurate measurement of heat flux described their applications and calibration needs. Presentations were made by

Fred Soechting of Pratt & Whitney, Joseph Coblish of Arnold Engineering Development Center (AEDC), Ned Keltner of Ktech Corporation, Kaveh Azar of Lucent Technologies, and Jeffrey Deane of Boeing Commercial Airplane Company. Lawrence Langley of Vatell Corporation led a panel of heat flux gauge manufacturers that included Larry Jones of Medtherm Corporation, Ludwig Holtermann of Concept Engineering, and Paul Siemiesz of RdF Corporation. Explanations and tours of NIST heat flux calibration laboratories were conducted by Robert Saunders, Carole Womeldorf, and William Grosshandler. Kenneth Steckler of NIST described the effort being undertaken in Europe to standardize heat flux calibration methods for fire safety standards. Discussions involving all the workshop participants, led by Kaveh Azar, Thomas Diller of Virginia Tech, and Ned Keltner, were organized around special considerations and calibration needs of heat flux measurement devices for three different situations: (1) convection dominated, moderate temperature, quasi-steady environments with size and cost as major constraints; (2) convection dominated, high temperature, transient environments with small size and accuracy highly desirable; (3) radiation dominated with high flux levels, with applications constrained by regulations.

INDUSTRY APPLICATIONS AND CALIBRATION NEEDS

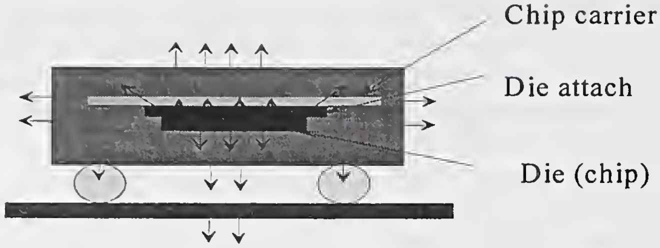
Heat Transfer in Convection Dominated, Moderate Temperature Environments (K. Azar, Lucent Technologies)

The electronics industry can be categorized into different sectors: consumer electronics, telecommunications, high end computers, and military/space applications. The common denominator which impacts the performance in all the segments is the junction temperature, which is determined by the heat transfer from the hottest point on the surface of the chip during normal operation. The desire for greater power densities continuously drives the need for more efficient heat transfer and higher heat fluxes in order to maintain the junction temperature within acceptable limits.

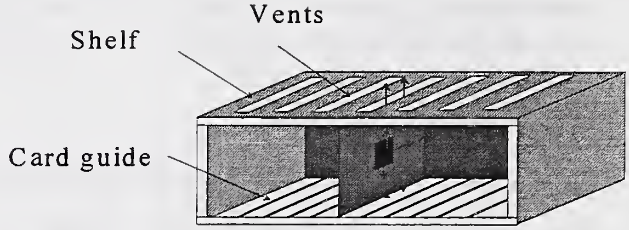
As a point of reference, a 100 W light bulb produces an average heat flux at its surface of about 9 kW/m^2. A telecommunication ball grid array (BGA) dissipating only 28 W produces a flux 15 times this value. The table below shows the device technology trend for the past four years. A factor of ten increase in the number of gates per device, a decrease in feature size of 30 %, and a five-fold increase in the frequency of a device over the past four years has resulted in a 20-fold increase in heat flux in spite of a factor of four drop in power required per gate.

Table 1. Recent advances in electronic device power parameters

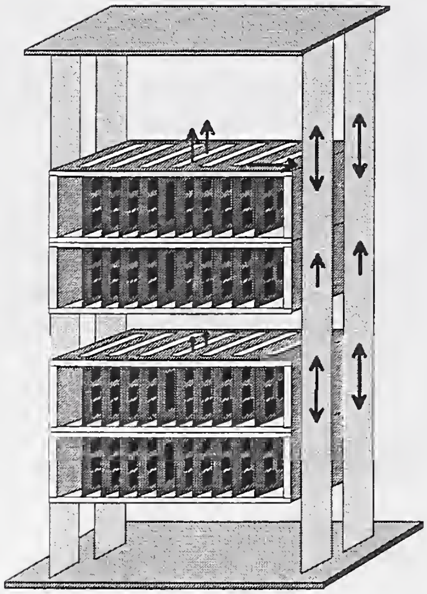
Year	No. Gates/Device	Feature Size (µm)	Voltage (V)	Power (µW/gate/MHz)
1995	$3x10^5$	0.35	3.3	0.64
1997	10^6	0.25	3.0	0.27
1999	$3x10^6$	0.25	2.5	0.15



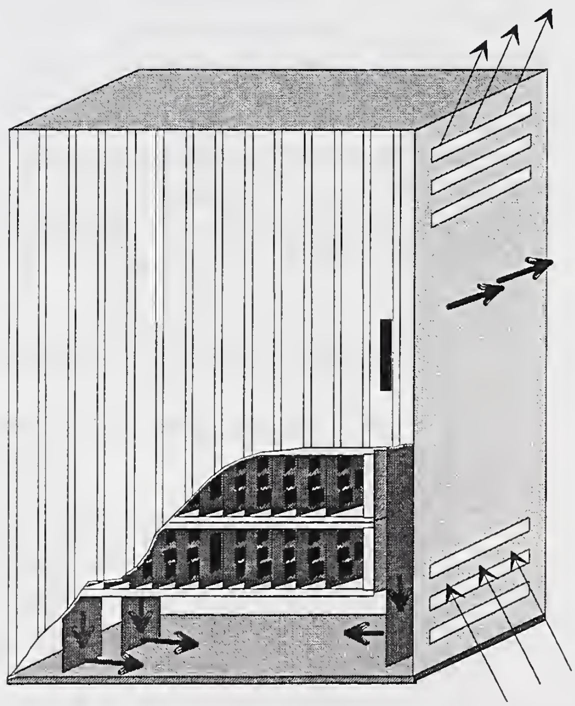
a. Component on card



b. Card rack

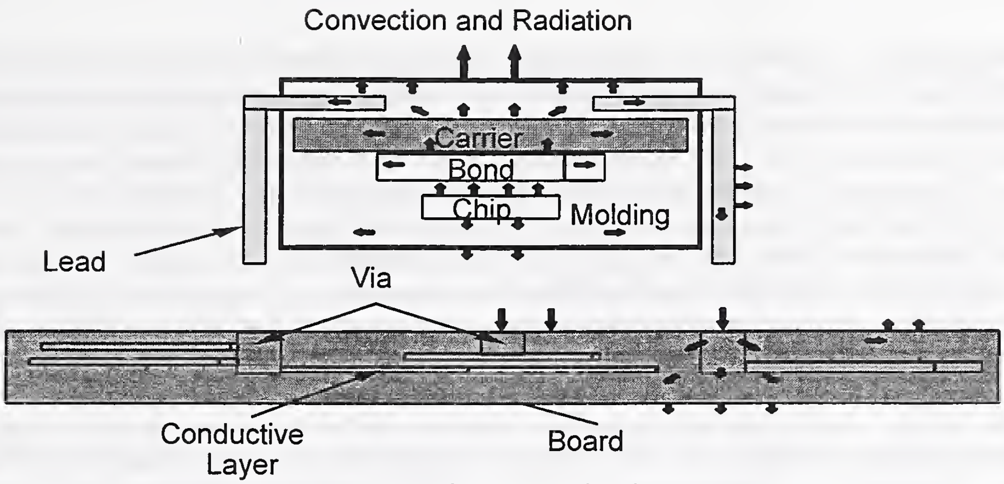


c. Frame

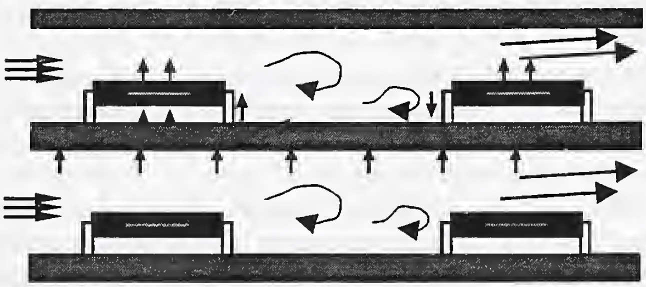


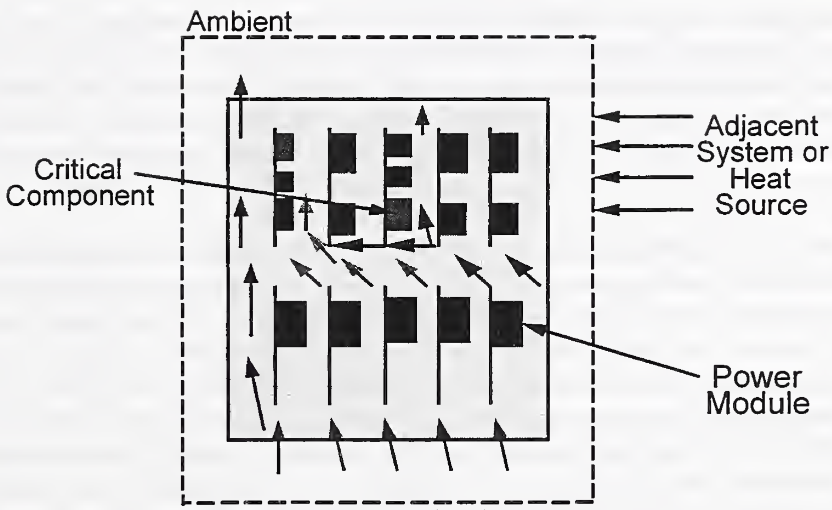
d. Cabinet

Figure 1. Multifaceted heat transfer in electronics enclosures



a. Component level


b. Board level



c. System level

Figure 2. Thermal challenges at multiple levels

For a design to be effective, one must consider not only the heat transfer from the chip to the card, but also from a single card to the rack, from the rack to the frame, from the frame to the cabinet, and from the cabinet to the environment. This hierarchy of heat transfer is shown in Figure 1. Figure 2 shows schematically more details of the heat transfer. At the component level, multiple heat paths exist through a high level of interconnection between the source and sink. The flow is three dimensional and with a large level of heat spreading. Conduction coupling occurs via the printed circuit board (PCB).
The different components on the board exchange heat convectively; heat is exchanged with adjacent boards by radiation and convection. Heat transfer to the mother board or card cage is by conduction. Convection, radiation and conduction thermal coupling occurs at all stages of the system. Thus, the heat transfer is multifaceted at a given point; the location and temperature of hot spots occur with unknown magnitude.

The challenge is to determine the junction temperature, and to predict how design changes are likely to reduce thermal coupling on the component. A simple thermal resistance model is useful to relate the junction temperature, T_J, to the air temperature, T_A, in terms of an effective resistance, R_{JA}, and the heat flux, q_{JA}: $T_J = q_{JA} R_{JA} + T_A$. Accurate determination of heat flux is pivotal for the calculation, which is why the heat flux sensor must be highly reliable. System level heat transfer measurements are required to identify the source and magnitude of thermal coupling within the system, and also of external loads as might occur from solar irradiation.

Heat flux measurement is a necessity. It is an essential element in thermal management of electronics systems. The industry is served better by making heat flux gauges as useful and as easy to use as a thermocouple, by greater size selection, by an ability to separate different modes of heat transfer with directionally sensitive devices, and by improved calibration.

For calibration, Lucent uses (1) conduction through a solid of known thermal conductivity which is in intimate contact with the heat flux gauge, and (2) convection from an isothermal block in the wall of a channel to determine the response of its gauges. The uncertainties in these measurements have not been quantified.

Heat Transfer in Convection Dominated, High Temperature Environments (F. Soechting, Pratt & Whitney; and J. Coblish, AEDC)

The trend in gas turbine designs used for power production and for jet propulsion is towards higher temperatures for the working fluid as a way to increase cycle efficiency and power-to-weight ratio. While the safe operating temperature of new materials used for turbine blades has increased substantially, it is still far below the peak gas temperature. Blade life is shortened by overheating, leading to more down-time and maintenance expense. Active cooling of the turbine blades is required to control the blade surface temperature, making the measurement and prediction of heat flux critical to the success of a given design.

Wright Patterson Air Force Base in Dayton, Ohio, houses a research facility capable of reproducing the thermal environments in gas turbine engines. Thin film gauges (Oxford and Dunn type) less than 50 μm thick and about 2.5 mm square are used to measure the heat flux on the turbine blades, typically up to 50 kW/m^2, as well as shear stress. [It would be desirable, as well, to measure the surface temperature remotely (e.g., with an optical fiber) to within ± 6 K.] The thermal contact resistance is not considered in interpreting the data. Experience has shown the repeatability of the heat flux gauges is about ± 7 %. Time response is important because of the transient nature of the heat transfer, and the importance of identifying the local transition between laminar and turbulent flow. Platinum layers 40 nm thick allow a frequency response up to 100 kHz. The decay rates are measured *in situ* by monitoring the application of a pulse of electrical current to the gauge. High accuracy steady-state calibration is not required for this type of calibration.

An order of magnitude higher heat flux (up to 500 kW/m^2) is encountered in hypersonic wind tunnels operated at AEDC. Local heat flux in blow-down facilities at Mach numbers up to 16.5 are generally measured using coaxial thermocouples. Coaxial thermocouple gauges are utilized due to their

quick time response (typically on the order of microseconds) and durability to the harsh environment. The measured surface temperatures are then inverted through a transient finite difference routine to obtain the applied heat flux. A possible source of error when using this technique is the selection of material thermal properties that are necessary to compute a heat flux level.

In the continuous flow facilities at AEDC, the direct-reading Schmidt-Boelter gauge is the preferred measurement technique. Even though the exposures of the sensors are primarily to compressible boundary layers, the primary calibration standard used at AEDC is the NIST radiation source. A quartz lamp is used on site as a secondary calibration standard. Recent work at AEDC has shown that a newly developed Schmidt-Boelter gage with a time response on the order of 10 ms can be used in transient applications. Papers by Kidd (1999) and Kidd and Scott (1999) provide details on the new measurement techniques and analysis developed at AEDC.

Heat Transfer in Radiation Dominated, High Flux Environments (N. Keltner, Ktech Corp.; and J. Deane, Boeing Commercial Airplane Co.)

The rate at which materials burn is controlled primarily by the feedback of radiation from the fire to the fuel surface. Depending upon the application, different government organizations dictate regulations that limit the burning rate at specified radiant fluxes. For example, the Coast Guard has responsibility for ships in U.S. waters and the FAA regulates the fire response of materials used on commercial aircraft.

Ktech Corp. recently characterized a test furnace for the Coast Guard used to reproduce the thermal insult to a bulkhead experienced in a shipboard fire. Ktech found that different furnaces produce histories of temperature that vary over 100 K and wall heat fluxes that differ by a factor of two. These large variations are due to a number of factors, including the furnace size and lining material, the control thermocouple design and location, the type of fuel used to fire the furnace, and the properties of the test specimen. An improved system for characterizing the thermal exposure of the specimen in the furnace was developed that utilizes a 1 m by 1 m metal plate instrumented with 25 sensors. The system can tolerate a temperature up to 1280 K. A nonlinear parameter estimation and one dimensional inverse heat conduction code are used to predict radiant heat fluxes that are within 20 % of the measured heat fluxes, such that the system is essentially self-calibrating. Uncertainties are associated with unknown material properties, exact thermocouple location, and thermocouple response.

Gardon gauges are approved by the FAA for setting the heat flux levels for aircraft materials testing. Because each new lot of material must pass a resistance-to-flammability test in order for the plane to be certified, aircraft manufacturers cannot tolerate an error when adjusting the heat flux levels that indicates the flux is within specification during the test, only to find in subsequent calibration the materials in question were subjected to heat fluxes below the minimum. Boeing has developed its own calibration method to insure compliance.

A radiation source is used that is composed of a low voltage, high current power supply (30 V @ 5000 A) and a graphite plate approximately 300 mm by 230 mm by 6 mm thick. The power supply is capable of heating the plate to approximately 1500 °C. A primary standard radiometer (TMI active cavity) placed 1 m from the graphite plate is used to measure the radiant emission, and assuming the emissivity is known (0.98), the temperature is calculated from Boltzmanns's law. A view limiting tube placed in front of the radiometer reduces stray emission and reflection. The Gardon gauge to be calibrated is placed in front of the radiometer facing the graphite plate. A water-cooled radiation absorber is positioned to prevent radiation from reflecting from the source to the gauge. By varying the distance of the gauge from the radiometer between 100 mm and 280 mm, one may vary the view angle and therefore the irradiation of the gauge. The voltage generated by the gauge is recorded as a function of the radiant flux, calculated from the geometry and temperature of the graphite plate. Heat fluxes up to 140 kW/m^2 are generated, although the radiometer is limited to 10 kW/m^2 by its aperture. The uncertainty of the radiometer is claimed by the user (Boeing Commercial Airplane Co.) to be within ± 10 %, controllable to 1 % when repeated. In application, the Gardon gauge is used to set the heat flux in the material test chamber to 35 kW/m^2, with measurements at the corner and center of the sample required to be in

agreement within 5 %. Uncertainties in the measured value of heat flux and non-uniform irradiation cause the operator to test materials at levels high enough to ensure the specimen is subjected to the minimum acceptable thermal stress.

CALIBRATION OF HEAT FLUX SENSORS FOR STANDARD FIRE TESTS (K. Steckler, NIST)

The ISO Plan

The International Standards Organization is developing a procedure for calibration and use of heat flux meters as it applies to fire testing (ISO, 1997). The group has found that convection effects are significant and unique to each standard fire test. The fire tests of concern specify the radiant flux that must be met for a particular configuration, but the gauges used measure the total heat flux. The question, then, is how the measurements in daily testing by various European fire laboratories relate to the regulation? The approach taken to answer this question is shown in Figure 3 and described in the following paragraphs.

The primary standard for radiant flux is a vacuum blackbody located at Laboratoire National D'essais (LNE) in France. A Gunners (Gunners,1967) ellipsoidal radiometer (or primary radiometer, PR) is used to measure the radiation from the primary source, and the output is compared to the response of a Schmidt-Boelter total heat flux gauge (or primary total heat flux gauge, PTHF) exposed to the same primary source.

The two primary detectors are shipped to the participating test laboratories in Europe, and are exposed to the laboratories' secondary source that consists of an atmospheric pressure spherical blackbody. By comparing the output of the Gunners radiometer to the Schmidt-Boelter total heat flux gauge, the convective component of the total heat flux produced in the secondary spherical blackbody can be estimated. The secondary blackbody is then used to calibrate a secondary total heat flux gauge (STHF).

There are three geometric configurations used extensively in fire testing: vertical [e.g., the LIFT (ASTM E 1321-97a) and OSU (ASTM E 906-98) apparatus], inclined [e.g., the HIFT apparatus (Montevalli, 1992)], and horizontal [e.g., the cone calorimeter (ASTM E 1354-97)]. The changing temperatures, view factors, placements with respect to the gravitational vector, and surrounding gas flows cause the importance of convection relative to radiation to vary considerably, which means the secondary total heat flux gauge response is also likely to vary relative to its response in the secondary calibration facility. To quantify this, the radiation component of each configuration is measured with the primary radiometer and the secondary total heat flux gauge, from which the output of the STHF can be calibrated *in situ* against the true radiative heat flux. The STHF can then be used in daily testing to set the proper radiant flux in each apparatus.

Proposed Adaptation to the U.S.

Fire testing in the U.S. is structured differently than in Europe, making direct application of the ISO approach unworkable. In the U.S., some testing is regulation-driven from a state or federal agency; some is for certifying by independent organizations such as Underwriters Laboratories; and some is science-driven to improve understanding or to develop new standards and measurement methods.

Calibration is currently distributed among the users and manufacturers of the heat flux gauges, but the responsibility for primary radiation standards in the U.S. traditionally has resided with NIST, and with the Physics Laboratory in particular. The NIST transfer standards are two gas-purged, cylindrical blackbodies operating over different temperature ranges and apertures, and are directly traceable to the NIST primary standard, the High Accuracy Cryogenic Radiometer (HACR). Convection is estimated to affect the calibration of heat flux gauges by less than 0.5 % as long as the distance between the gauge

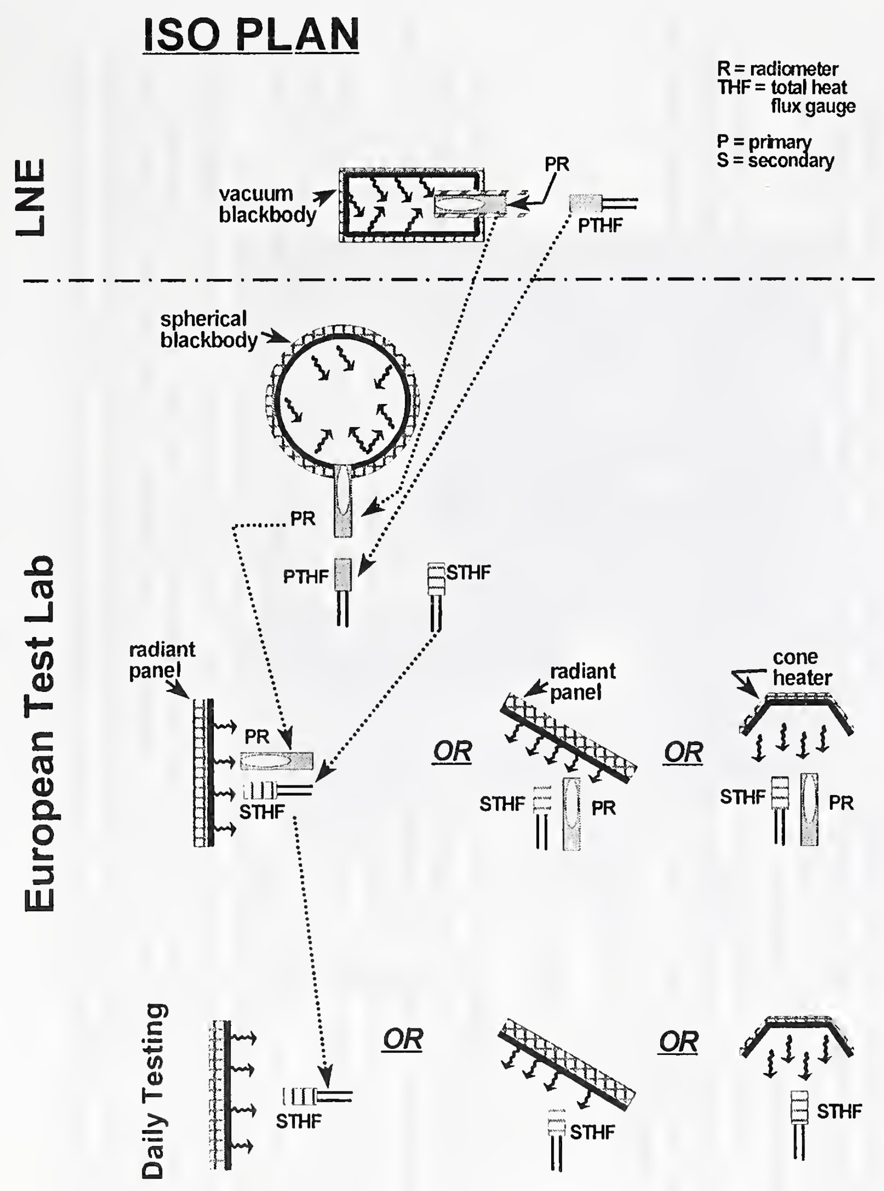


Figure 3. ISO plan for calibrating heat flux gauges for fire testing

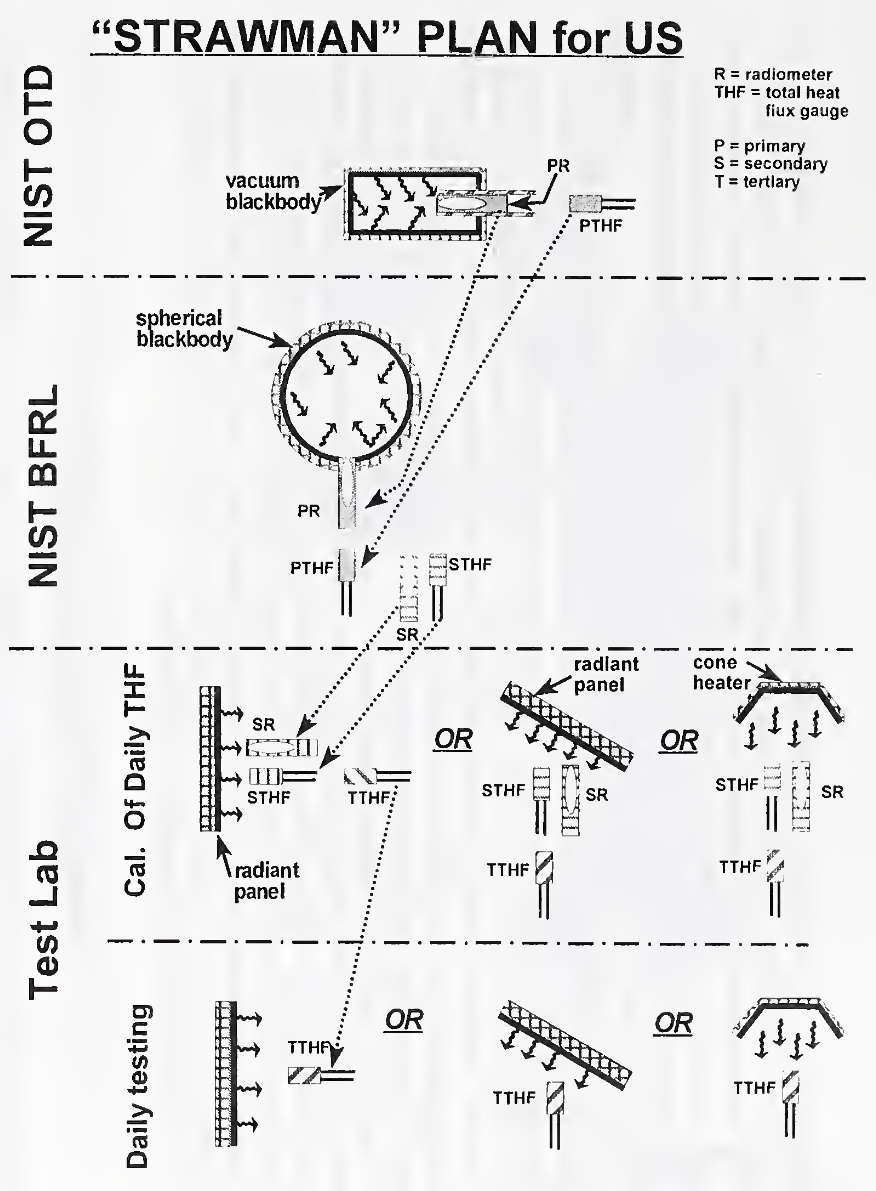


Figure 4. Proposed calibration chain for U.S. fire testing labs

and the opening of the blackbody is greater than some minimum length. To duplicate the maximum heat flux levels and view factors observed in many fire tests, however, the gauge needs to be placed closer than this distance to the furnace opening, increasing the uncertainty caused by unknown convective heat transfer. Nonetheless, the NIST gas-purged blackbodies can be used as the transfer standard for calibrating a primary radiometer and total heat flux gauge as is done in the ISO procedure, but with a greater level of estimated error.

Many European countries maintain their own national fire laboratories that are distinct from LNE. The Building and Fire Research Laboratory at NIST, however, is *the* national fire laboratory in the U.S. The equivalent of the spherical blackbody, used as a secondary radiation standard in Europe, is located in the NIST Physics Laboratory, not in BFRL. Independent of where the spherical blackbody is located, it can serve as a secondary source for calibrating a NIST secondary radiometer and total heat flux gauge by checking against the primary radiometer and total heat flux gauge calibrated with the NIST primary standard. The secondary radiation and total heat flux gauge serve the same purpose in the proposed U.S. plan as in the ISO method: to estimate the convective component in the secondary radiation standard, and to relate the total flux measured in actual testing apparatus to the prescribed radiation. A tertiary total heat flux gauge (TTHF) can be calibrated in BFRL with the STHF in the configuration desired. The TTHF then becomes the reference gauge for daily testing, conducted either at NIST or in the field. The user or manufacturer could come to NIST for primary, secondary, or tertiary gauge (radiative or total heat flux) calibration services on a schedule to be determined. Figure 4 is a flow diagram of the proposed U.S. method, relating the primary, secondary and tertiary devices.

NIST HEAT FLUX CALIBRATION FACILITY

The ability to produce a primarily conductive or radiative boundary condition at the interface between a gas and the surface in which a heat flux gauge is mounted has been developed in the new NIST heat flux calibration facility. The desired radiation flux is generated by the three different electrically heated blackbody furnaces. Figure 5 shows the 25 mm graphite tube variable temperature blackbody and the recently developed spherical blackbody. The larger 51 mm graphite blackbody (not shown) is similar in structure to the 25 mm blackbody.

Figure 6 is a schematic of the convection wind tunnel, and Figure 7 shows a cross-section of the conduction rig. Complete details on each of these calibration devices are published in the NIST *Journal of Research* (Murthy et al., Grosshandler et al., Holmberg et al.). Table 2 summarizes the capabilities and specifications of the facility.

HEAT FLUX GAUGE MANUFACTURERS' PERSPECTIVE

Design and manufacturing activities in the U.S. heat flux gauge industry are limited to a relatively few small companies. Lawrence Langley of Vatell Corporation organized a panel of representatives from several of them (Concept Engineering, Medtherm Corp., and RdF Corporation) to discuss heat flux device calibrations and problems. Each manufacturer maintains its own calibration facility, based upon blackbody radiation and/or approximately one-dimensional conduction through a material with known thermal conductivity. RdF (which has absorbed HyCal) uses a reference therompile and radiation source for flux levels up to 227 kW/m^2. For total heat flux gauges at low levels, RdF calibrates to 1.1 kW/m^2 by comparing the voltage from the gauge pressed against the surface of a solid of known thermal conductivity to the temperature gradient in the solid. Concept Engineering is concerned primarily with low heat flux level devices. They base their calibration on a NIST-certified commercially produced radiation source maintained at 670 K. For calibrating in the conduction mode, they use a guarded hot plate system (ASTM C 177) and NIST Standard Reference Materials (SRMs). Vatell (now combined with the former Thermogage, Inc.) calibrates its high flux sensors with two different radiation sources:

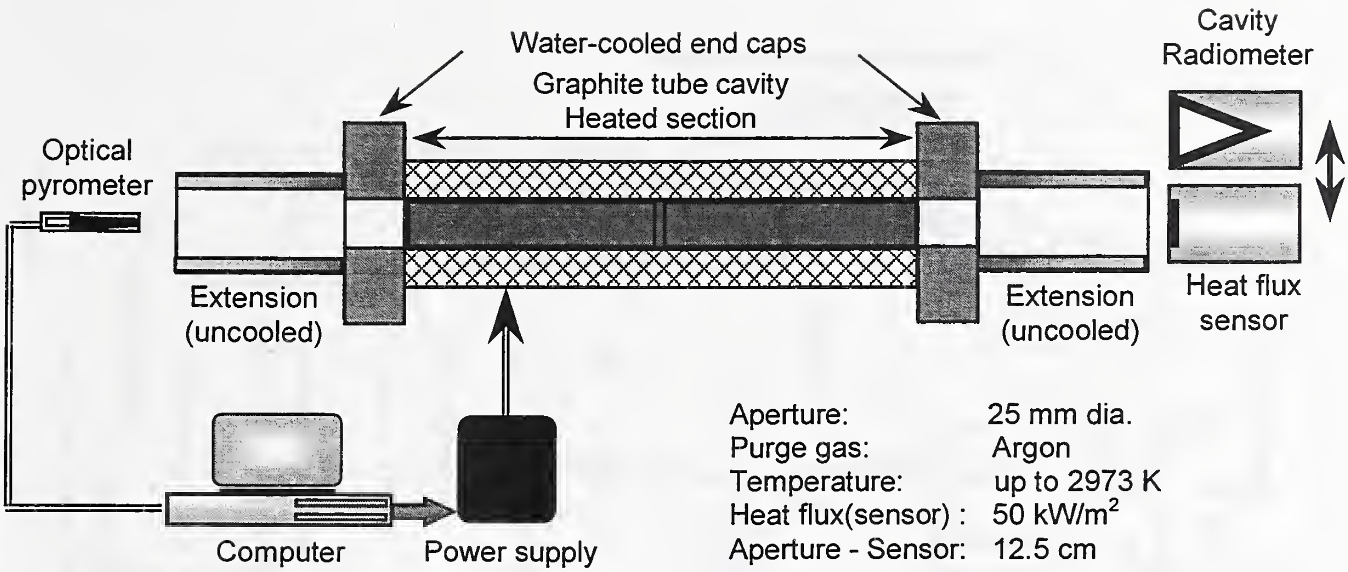


Figure 5a. 25 mm variable temperature blackbody used in NIST radiation calibration facility

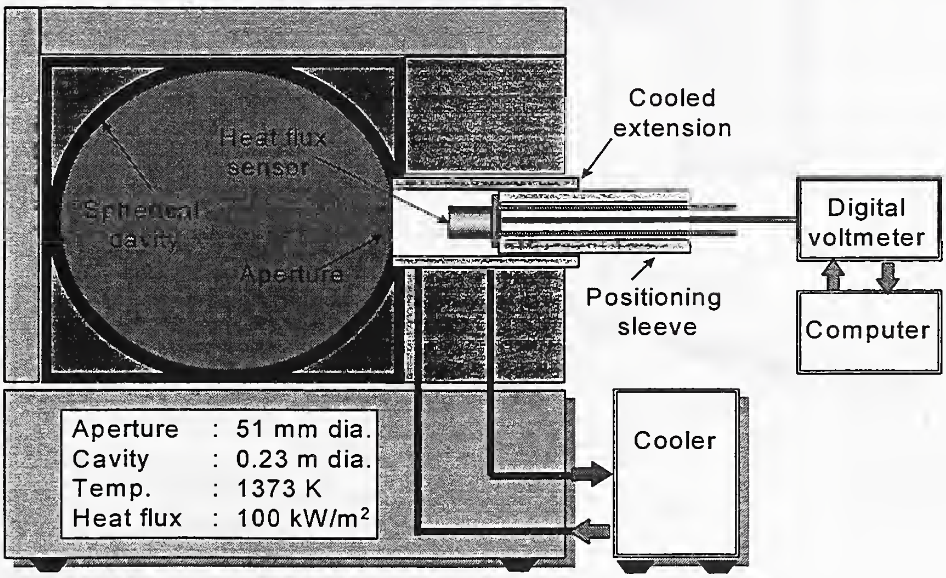


Figure 5b. Spherical blackbody used in NIST radiation calibration facility

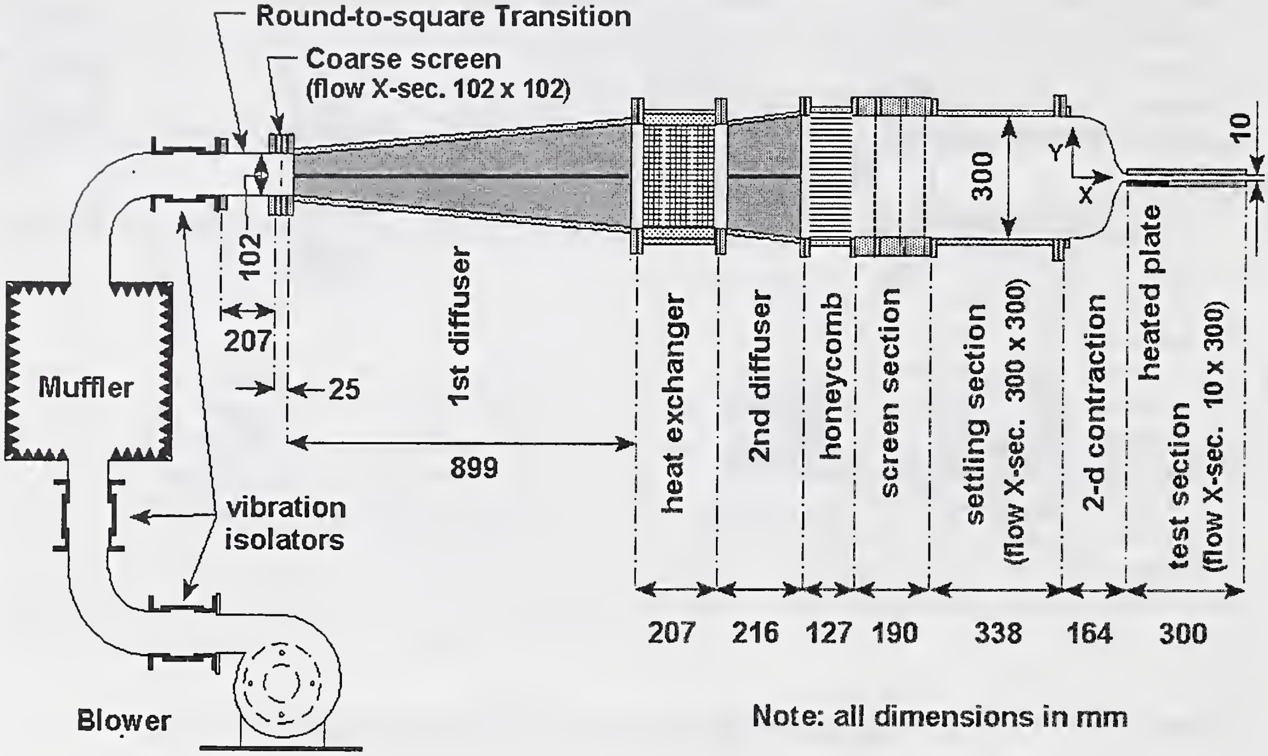


Figure 6a. Schematic of NIST convective heat transfer calibration tunnel

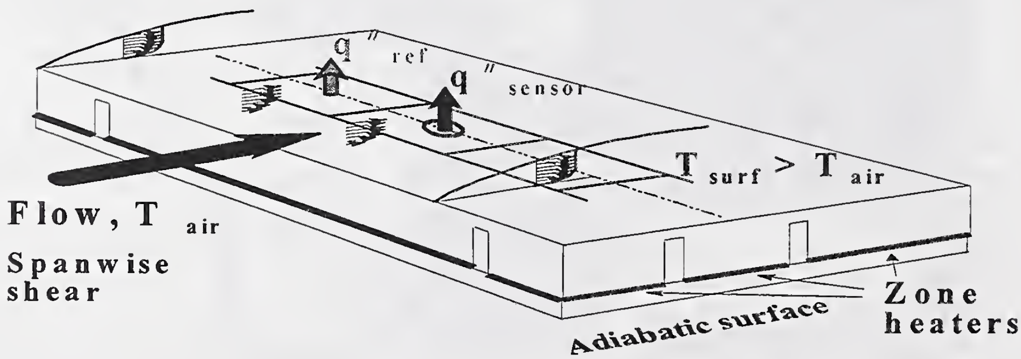


Figure 6b. Boundary layer flow over test section hot plate in convective heat transfer tunnel

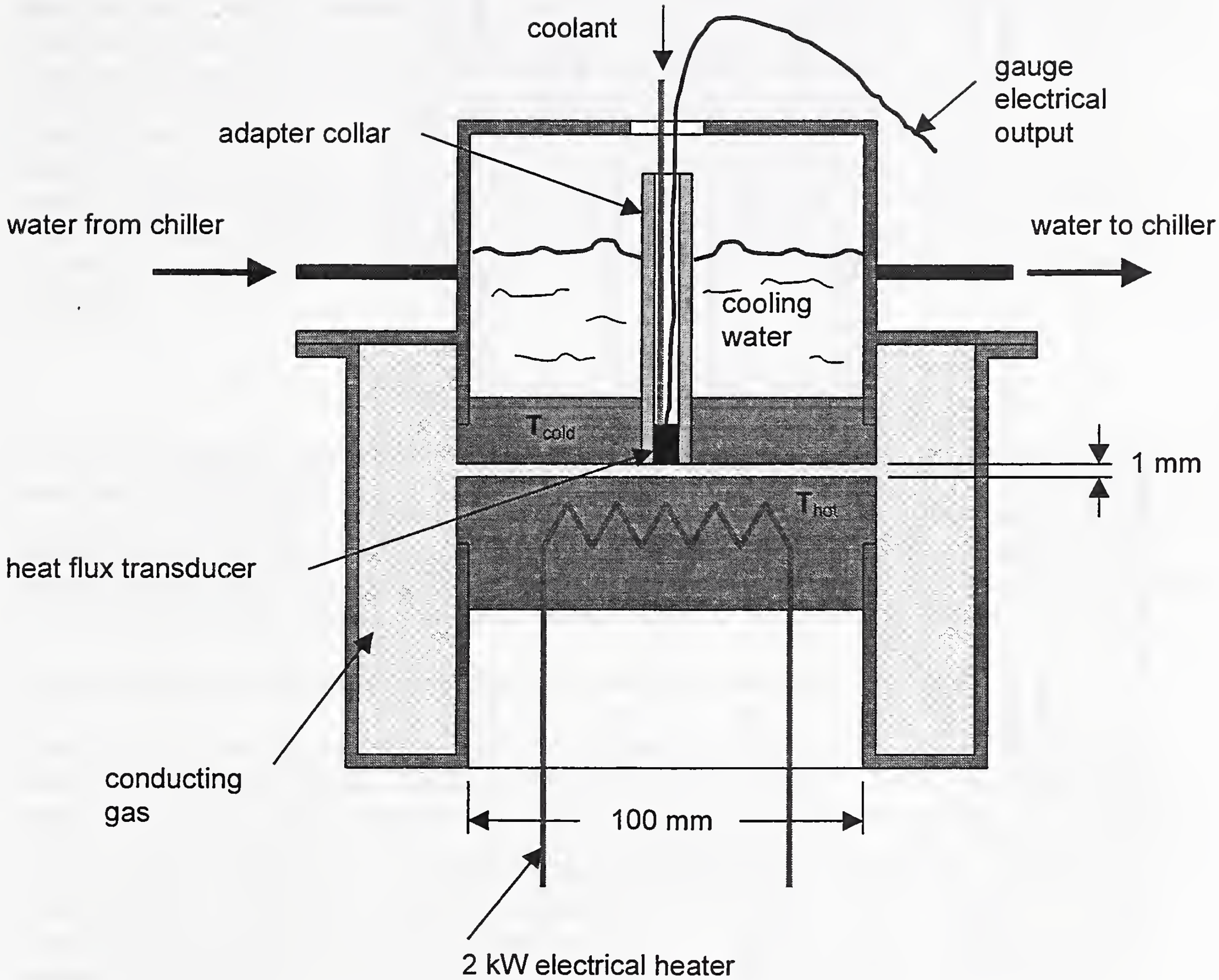


Figure 7. Schematic of NIST high heat flux conduction apparatus

Table 2. Current capabilities of NIST single mode heat flux calibration facilities

Mode	Flux Levels kW/m^2	Expanded Uncertainty, 95 % Confidence Level	Conditions	Gauge Style Accommodated (D = maximum body diameter)
Conduction	1 to 75	< 10 %	sensor temperature from 275 K to 375 K, in N_2 or He from 1 kPa to 200 kPa	D < 12.5 mm; flat surface (± 0.1 mm); cooled or uncooled, button or foil type
Convection	0.1 to5	< 2 %	sensor temperature from 295 K to 375K, in ambient air flowing up to 30 m/s	D <2 5 mm; flat surface (± 0.1 mm); cooled or uncooled, button or foil type
Radiation, High Temperature Blackbodies	< 60	< 2 %	T < 3000 K, D < 50 mm, restricted view, in ambient air	D < 50 mm; cooled or uncooled; button, foil, or cavity type; w/wo windows
Radiation, Spherical Blackbody	< 100	< 3 %	T < 1300 K, D < 50 mm, view approaching 150°, in cooled enclosure	D<50 mm; cooled; button or foil type; w/wo windows

(1) a light source traceable to NIST using the substitution method, and (2) an electrically heated plate maintained at a predetermined temperature, with a reference sensor viewing one side of the plate and the sensor to be calibrated viewing the other. Vatell also fabricates a large area gauge, 0.3 m on a side, which is calibrated via conduction using the guarded hot plate approach (ASTM C177).

Medtherm (1995) has established a procedure for radiant calibration up to 6700 kW/m^2 for heat flux gauges and infrared radiometers that includes multiple radiation sources. The primary sources are metal freezing point blackbodies, variable temperature electrically heated blackbody cavities, and vacuum blackbodies, with the fluxes from each determined from temperature measurements with a calibrated thermocouple or radiation thermometer traceable to NIST. For production calibration, a total irradiance lamp bank and graphite plate graybody are used. The irradiance from the lamps is checked by the lamp manufacturer, and is traceable to a NIST standard. The graphite plate is similar to the device used by the other heat flux gauge manufacturers. The uniformity of temperature over its surface is determined in steady state with a narrow-view radiometer calibrated with one of the Medtherm blackbodies. The graphite plate and lamp bank are used during production to provide a view factor closer to the acceptance angle of the heat flux gauge. Ellipsoidal cavity radiometers are calibrated by total insertion into a spherical blackbody which irradiates the cavity approximately uniformly over a close to 180 ° angle of view. The impact of natural convection on the process is minimized by performing the calibration with the gauge facing upward. The capability to check the gauge with its sensing surface parallel to gravity also exists.

SUMMARY OF CALIBRATION NEEDS

Issues were identified at the workshop that were common to a number of users and manufacturers, and that impact on calibration procedures. The needs discussed below and summarized in Table 3 are categorized by application: (1) convection dominated, moderate temperature, quasi-steady environments with size and cost as major constraints; (2) convection dominated, high temperature, transient environments with small size and accuracy highly desirable; and (3) radiation dominated with high flux levels, with applications constrained by regulations.

Heat Transfer In Convection Dominated, Moderate Temperature Environments

The flows of primary interest in this category involve near room temperature air at low Mach number, fan-driven and naturally buoyant, laminar and turbulent, with quasi-steady heat transfer occurring from a heated solid surface. The most challenging measurements are localized on three-dimensional electronic components, with significant conduction into non-homogeneous and non-isotropic circuit boards, spaced to form narrow passages. For proper thermal management of electronic cabinets, heat transfer from the flat, external walls, with and without solar radiation, must also be measured. The sensing elements for these kinds of measurements typically range from 12 mm on a side to below 1 mm, they are fully exposed, uncooled, thin foil in construction, and with emissivities well below unity. Calibration in a convective environment is required, with some feel for response to short wave (solar) and long wave radiation.

An uncertainty of ± 8 % of measured value is desirable. Time response is not critical, although susceptibility to noise from adjacent electronics reduces usefulness of data. The number of devices needed, their cost, and the modest level of accuracy required indicate that calibration at the user's laboratory with a convective flow is most appropriate. A heat flux gauge of similar construction could act as a tertiary reference for the convection source. The reference gauge response should be traceable to the NIST convection tunnel. The radiation response (at long and short wavelengths) of the production gauges could be provided by the manufacturer at the time of purchase. Additional experience with the NIST tunnel and field measurements needs to be acquired before a calibration schedule can be recommended or cost per calibration determined.

Table 3. Requirements for Heat Flux Gauge Calibration Facilities

Application Category and Environment	Gauge Types			Calibration Mode, with expanded relative uncertainty at 95 % confidence level			Static, Dynamic	Primary, Second., Tertiary	Frequency, Turnaround
	Range of sizes, mm	Cooled?	Surface	Radiation	Convection	Conduction			
Convection Dominated, Moderate Temperature	0.1 to 25	no	full view $\epsilon < 0.9$	supplement	> 10 kW/m^2 ± 2 %	supplement	Static	*S, T*	*S,T* > 1/yr 15 days
Convection Dominated, High Temperature	0.1 to 25	no	full view $\epsilon < 0.9$	>100 kW/m^2 ± 3 %	>100 W/m^2 ± 3 %	supplement	Dyn.[a]	*P, T*	*P* < 1/yr 30 days
Radiation Dominated, High Flux	1.0 to 25	yes and no	variable view, $\epsilon > 0.9$ w/wo window	>10^3 kW/m^2 ± 2 %	> 10 kW/m^2 ± 2 %	supplement	Static	*P, S, T*	*P* < 1/yr 30 days *S,T* > 1/yr 15 days
Conduction	0.1 to 500	no	full view $\epsilon < 0.9$	no	no	< 1 kW/m^2 ± 2 %	Static	*S* SRM[b]	*S* < 1/yr 30 days

[a] *in situ* calibration required
[b] Standard Reference Material

Heat Transfer in Convection Dominated, High Temperature Environments

Prime examples of this type of environment are turbine blades in subsonic flow of combustion products and aerodynamic heating of bodies in supersonic flow. Schmidt-Boelter and thin foil type gauges are used for these measurements. They are most often 12 mm in diameter or smaller and the sensing surface is fully exposed to the flow. Radiation can be significant because of the high temperatures involved.

A specific accuracy goal was not selected, but because of the economic benefit of operating high speed machinery and reentry vehicles within a narrow range around the design limits of the materials, the ability to interpret the signal from the sensing device with certainty is highly desirable. Simultaneous measurement of the gauge temperature can improve accuracy. Time response in the microsecond to millisecond range is required. At the other extreme, precise calibration of the sensor exposed to a steady heat flux is of little value.

The close coupling between the response of the sensor, the substrate on which it is mounted, and the extreme conditions in which the measurements are taken make controlling a similar environment for calibration purposes technically difficult (and expensive) at best, and futile at worst. *In situ* calibration of each sensor is preferred. Possible methods include simultaneous inversion of multiple temperature and heat flux signals, the inclusion of a heater in the gauge which responds to a short electrical pulse, exposure of the sensor to pulsed laser radiation, or some combination. While a calibration path traceable to NIST primary radiation and temperature standards is desirable, the major calibration issues need to be worked out with the government laboratories where the test facilities are located (e.g., DOD and NASA).

Heat Transfer in Radiation Dominated, High Flux Environments

Radiation often dominates the heat transfer process when combustion is involved. This is the case for materials fire testing. However, convection is always present during combustion and its effect needs to be considered. Flow velocities can vary from less than 1 m/s up to sonic conditions. The heat flux to be measured may be to an open boundary (e.g., around a pool fire), to a cooled wall (e.g., steam tubes in a furnace), or to a wall without water cooling (e.g., a gas turbine combustor liner or a refractory-lined furnace). Water-cooled Gardon and Schmidt-Boelter gauges, with and without windows, are common in these applications, and contamination of the sensor often occurs. Radiation calibration is essential over the spectral range and view angle encountered during the measurement. The convection calibrator can be used for low flux levels, and the conduction apparatus used for the higher fluxes. If the response of the gauge is much different to heat conducted through a boundary layer than to radiation absorbed in the surface, the specific application needs to be analyzed to properly estimate the uncertainty of the measurement.

As in the other applications, the more accurate the heat flux measurement, the closer to the performance limit the system can be designed/operated. A ±10 % uncertainty in heat flux for the duration of the measurement is suggested as a goal in the absence of degradation due to contamination of the sensing element. Time response is usually less of a concern, with transients normally of the order of 1 s. For some applications (e.g., following radiation/turbulence interactions), response times below a millisecond are required.

Many of the applications for radiation dominated heat flux measurements are tied to a mandated test method, with calibration schedules dictated by the regulating agency. The calibration chain suggested in Figure 4 is one approach, with the frequency determined by the discrepancies encountered between calibrations.

RECOMMENDED ACTIONS

NIST

- Prepare a plan to refine the calibration procedure outlined in Figure 4 to better serve the needs for U.S. materials fire testing. (BFRL)

- Develop a high temperature vacuum blackbody as the primary U.S. radiative flux standard up to 200 kW/m^2, with an expanded uncertainty (95 % confidence level) of ± 0.5 %. (PL)

- Develop a secondary radiation standard based upon the spherical blackbody that can be used to calibrate wide angle total heat flux gauges and radiometers up to 100 kW/m^2 as tertiary reference gauges, with an expanded uncertainty (95 % confidence level) of ± 2 %. (BFRL)

- Utilize the conduction calibration apparatus to determine the influence of three-dimensional heat transfer on discrepancies between calibration methods. (BFRL)

- Establish a protocol for calibrating tertiary heat flux gauges in the NIST convection tunnel. (BFRL)

Industry

- Refine the development of a wind tunnel suitable for routine calibration of thin foil heat flux gauges, with performance traceable to the NIST convection rig. (Lucent)

- Standardize procedures for calibrating heat flux gauges used in gas turbine engines. (Pratt & Whitney, with AFRL)

- Standardize procedures for routine, daily calibration of heat flux gauges used in materials fire testing, with performance traceable to NIST standards. (Boeing, U.L., Omega Point, Southwest Research, Factory Mutual)

Other Agencies

- Identify and overcome barriers to adoption of improved heat flux calibration standards. (DOT)

- Determine means to extrapolate to flux levels greater than range of calibration and to correct for mixed modes of heat flux under operational conditions. (NASA, DOD, DOE)

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